LCA CASE STUDY · DISCUSSION ARTICLE

Life-cycle assessment of a 2-MW rated power wind turbine: CML method

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Abstract
Background, aim and scope Renewable energy sources nowadays constitute an increasingly important issue in our society, basically because of the need for alternative sources of energy to fossil fuels that are free of CO_2 emissions and pollution and also because of other problems such as the diminution of the reserves of these fossil fuels, their increasing prices and the economic dependence of non-producers countries on those that produce fossil fuels. One of the renewable energy sources that has experienced a bigger growth over the last years is wind power, with the introduction of new wind farms all over the world and the new advances in wind power technology. Wind power produces electrical energy from the kinetic energy of the wind without producing any pollution or emissions during the conversion process. Although wind power does not produce pollution or emissions during operation, it should be considered that there is an environmental impact due to the manufacturing process of the wind turbine and the disposal process at the end of the wind turbine life cycle, and this environmental impact should be quantified in order to compare the effects of the production of energy and to analyse the possibilities of improvement of the process from that point of view. Thus, the aim of this study is to analyse the environmental impact of wind energy technology, considering the whole life cycle of the wind power system, by means of the application of the ISO 14040 standard [ISO (1998) ISO 14040. Environmental management—life cycle assessment—principles and framework. International Standard Organization, Geneva, Switzerland], which allows quantification of the overall impact of a wind turbine and each of its component parts using a Life Cycle Assessment (LCA) study.
Materials and methods The procedures, details, and results obtained are based on the application of the existing international standards of LCA. In addition, environmental details and indications of materials and energy consumption provided by the various companies related to the production of the component parts are certified by the application of the environmental management system ISO 14001 [ISO (2004) ISO 14001 Environmental management systems—requirements with guidance for use. International Standard Organization, Geneva, Switzerland]. A wind turbine is analysed during all the phases of its life cycle, from cradle to grave, by applying this methodology, taking into account all the processes related to the wind turbine: the production of its main components (through the incorporation of cut-off criteria), the transport to the wind farm, the subsequent installation, the start-up, the maintenance and the final dismantling and stripping down into waste materials and their treatment. The study has been developed in accordance with the ISO 14044 standard [ISO (2006) ISO 14044: Environmental management—life cycle assessment—requirements and guidelines. International Standard Organization, Geneva, Switzerland] currently in force.

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Results The application of LCA, according to the corresponding international standards, has made it possible to determine and quantify the environmental impact associated with a wind turbine. On the basis of this data, the final environmental effect of the wind turbine after a lifespan of 20 years and its subsequent decommissioning have been studied. The environmental advantages of the generation of electricity using wind energy, that is, the reduction in emissions and contamination due to the use of a clean energy source, have also been evaluated.

Discussion This study concludes that the environmental pollution resulting from all the phases of the wind turbine (manufacture, start-up, use, and dismantling) during the whole of its lifetime is recovered in less than 1 year.

Conclusions From the developed LCA model, the important levels of contamination of certain materials can be obtained, for instance, the prepreg (a composite made by a mixture of epoxy resin and fibreglass). Furthermore, it has been concluded that it is possible to reduce the environmental effects of manufacturing and recycling processes of wind turbines and their components.

Recommendations and perspectives In order to achieve this goal in a fast and effective way, it is essential to enlist the cooperation of the different manufacturers.

Keywords CML method · Copper · Discussion article · Electricity · Energy production · LCA case study · Wind energy farms · Wind turbine

1 Background, aim and scope

Renewable energy sources constitute an alternative to fossil fuels and their problems, which are, on the one hand, the pollution and CO_2 emissions that they produce and, on the other hand, the diminution of reserves, in addition to other economical and political problems, such as their increasing prices and the economic dependence of non-producers countries on those that produce fossil fuels.

One of the renewable energy sources that has experienced a bigger growth over the last years is wind power, with the introduction of new wind farms all over the world and the new advances in wind power technology that have made this source more and more efficient.

Wind power produces electrical energy from the kinetic energy of the wind without directly producing any pollution or emissions during the conversion process, but this does not means that it is free of contamination or CO_2 emissions. The question is that it should be considered that there is an environmental impact due to the manufacturing process of the wind turbine and the disposal process at the end of the wind turbine life cycle. And this environmental impact should be quantified in order to compare the effects of the production of energy and to analyse the possibilities of improvement of the process from that point of view.

Thus, the aim of this study is to analyse the environmental impact of the wind energy technology, considering the whole life cycle of the wind power systems. The application of the ISO 14040 standard (ISO 1998) allows us to quantify the overall impact of a wind turbine and each of its components from a Life Cycle Assessment (LCA) study. It also allows us to analyse the issues that produce more impact and the aspects that could be improved in order to reduce the effective impact.

The LCA model has been developed with the purpose of determining and quantifying the related emissions and the impact of wind energy production technology; in addition, the LCA model can be used to define the energy payback time.

At the present time, renewable energy, and particularly wind power energy, is becoming increasingly relevant in the world's electricity market based on its advances and on the legislative support of governments in several countries (del

Fig. 1 Evolution and future objectives for wind power installments
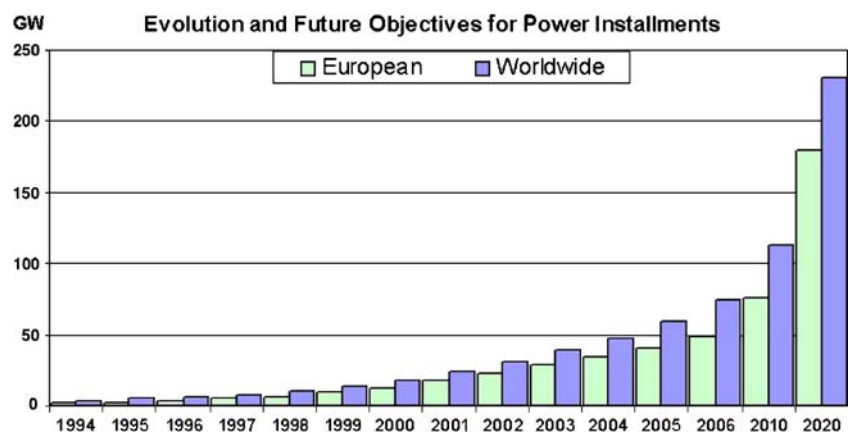
Río and Unruh 2007; Jäger-Waldau 2007; Karki 2007; Breukers and Wolsink 2007), for instance, with legal frameworks presenting stable and lasting premiums. Figure 1 shows the contribution and the provisions of wind power to the electricity supply network in several countries, both at a European and world level; current forecasts predict that wind power will contribute 12% of the global demand for electricity by 2020 (GWEC 2005). This huge boom in implementation and forecasts of this power source justify the need to increase its people's understanding (Jungbluth et al. 2005; Gurzenich et al. 1999) based on scientific studies, especially from the point of view of its environmental impact.

Within the existing LCA studies, there are several ones based on renewable energies in general (Gurzenich et al. 1999; Góralczyk 2003), which do not analyse in detail the LCA of a wind turbine. Gurzenich et al. (1999), for instance, shows (in its Section 2) a comparison of the results of several renewable energy sources, without actually explaining in detail the LCA made in each case, and then focuses on the development of dynamic life cycle assessment as a central part of the study. There are also more specific studies on wind turbines, but they are generally based on older machines and lower rated power, less than 1 MW (Celik et al. 2007; Jungbluth et al. 2005; Ardente et al. 2008), or they refer to hybrid technologies (Khan et al. 2005). In Celik et al. (2007), micro-turbines and low power urban installation, for example, are studied. Jungbluth et al. (2005) analyses the rapprochement of the database Ecoinvent to wind powers, focusing on studying wind turbines with power ranges from 30 to 800 kW. Ardente et al. (2008) deepens in the LCA of a wind farm with 11 turbines of 660-kW rated power. Khan et al. (2005) develops an LCA on a hybrid system of wind turbine with fuel cells, with a wind turbine of 500-kW rated power. In addition to these studies about low-power turbines, there are also other analyses focused on multi-megawatt wind turbines, as for instance, Tryfonidou and Wagner (2004) and Douglas et al. (2008), both of which are focused on offshore wind turbines. On the other hand, there are indeed studies based on multi-megawatt wind turbines, but basically outside the LCA point of view, and focused exclusively on the potential of wind generation of certain areas or regions (Ben Amar et al. 2008; Carolin Mabel and Fernandez 2008; Wichser and Klink 2008).

2 Methodology

2.1 Method and scope

LCA methodology based on CML Leiden 2000 was used in this study to avoid subjectivity (Guinée et al. 2001). The midpoint impact categories considered have been:

- Abiotic depletion: This impact category is concerned with protection of human welfare, human health and ecosystem health and is related to extraction of minerals and fossil fuels due to inputs in the system. The abiotic depletion factor is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration of reserves and rate of deaccumulation (Goedkoop et al. 2004).

- Climate change: Climate change can result in adverse affects upon ecosystem health, human health and material welfare and is related to emissions of greenhouse gases to air. The climate change factor is expressed as global warming potential for 100 years time horizon, in kg carbon dioxide/kg emission (Goedkoop et al. 2004).

- Stratospheric ozone depletion: This category is related to the fraction of UV-B radiation reaching the earth surface. The characterisation model is developed by the World Meteorological Organisation and defines the ozone depletion potential of different gasses (kg CFC-11 equivalent/kg emission) (Goedkoop et al. 2004).

- Human toxicity: This impact category is related to exposure and effects of toxic substances for an infinite time horizon. For each toxic substance, human toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission (Goedkoop et al. 2004).

- Fresh-water aquatic eco-toxicity: This impact category is related to the impact on freshwater ecosystems as a result of emissions of toxic substances to air, water, and soil, for an infinite time horizon. For each toxic substance, eco-toxicity potential is expressed as 1, 4-dichlorobenzene equivalents/kg emission (Goedkoop et al. 2004).

- Marine eco-toxicity: This impact category is related to the impact on marine ecosystems. As in the human toxicity category, the eco-toxicity potential is expressed as 1, 4-dichlorobenzene equivalents/kg emission (Goedkoop et al. 2004).

- Terrestrial eco-toxicity: This impact category is related to the impact on terrestrial ecosystems. As in the human toxicity category, the eco-toxicity potential is expressed as 1,4-dichlorobenzene equivalents/kg emission (Goedkoop et al. 2004).

- Photochemical oxidation: This category is related to the formation of reactive substances (mainly ozone) that are injurious to human health and ecosystems and which may also damage crops. The impact potentials are expressed as an equivalent emission of the reference substance ethylene, C_2H_4 (Hauschild and Wenzel 1998).

- Acidification: This category is related to the acidifying substances that cause a wide range of impacts on soil,

groundwater, surface water, organisms, ecosystems and materials. The major acidifying substances are SO_2, NO_X, HCl and NH_3. For emissions to air, the acidification potential is defined as the number of H^+ ions produced per kg substance relative to SO_2 (Bauman and Tillman 2004).

- Eutrophication: This category is related to all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Nitrogen (N) and phosphorus (P) are the two nutrients most implicated in eutrophication. Eutrophication potentials are often expressed as PO_4^- equivalents (Bauman and Tillman 2004).

In addition, an energy input assessment was carried out using cumulative energy demand (CED) to calculate the total direct and indirect amount of energy consumed throughout the life cycle (Boustead and Hancock 2003; Pimentel 2003).

The software used in the environmental analysis was SimaPro 7.0 by Pré Consultants (SimaPro 2006).

A LCA model of a wind turbine with double-feed inductor generator (DFIG) has been developed with the objective of identifying the main types of environmental impact throughout the life cycle, in order to define possible ways of achieving environmental improvements for the particular type of wind turbine analysed, or for similar ones. The wind turbine is a Gamesa onshore wind turbine, G8X model, with 2-MW rated power, and general dimensions: 80 m rotor blade, 5,027 m² sweep area and 70 m height.

The wind turbine is installed in the Munilla wind farm, in northern Spain, where it has been analysed during the different stages of its life cycle, from cradle to grave, taking into consideration the production of each of its component parts, the transport to the wind farm, the installation, the start-up, the maintenance and final decommissioning, with its subsequent disposal of waste residues (Fig. 2).

2.2 System boundary

Within the limits of the system studied fall the construction of the main components of the turbine, the transportation of the turbine to the wind farm, the assembly, the installation and the start-up, as well as the process of dismantling the wind turbine and the subsequent treatment of generated waste.

Outside the limits of the system under study fall the system of distribution of the electricity generated by the wind

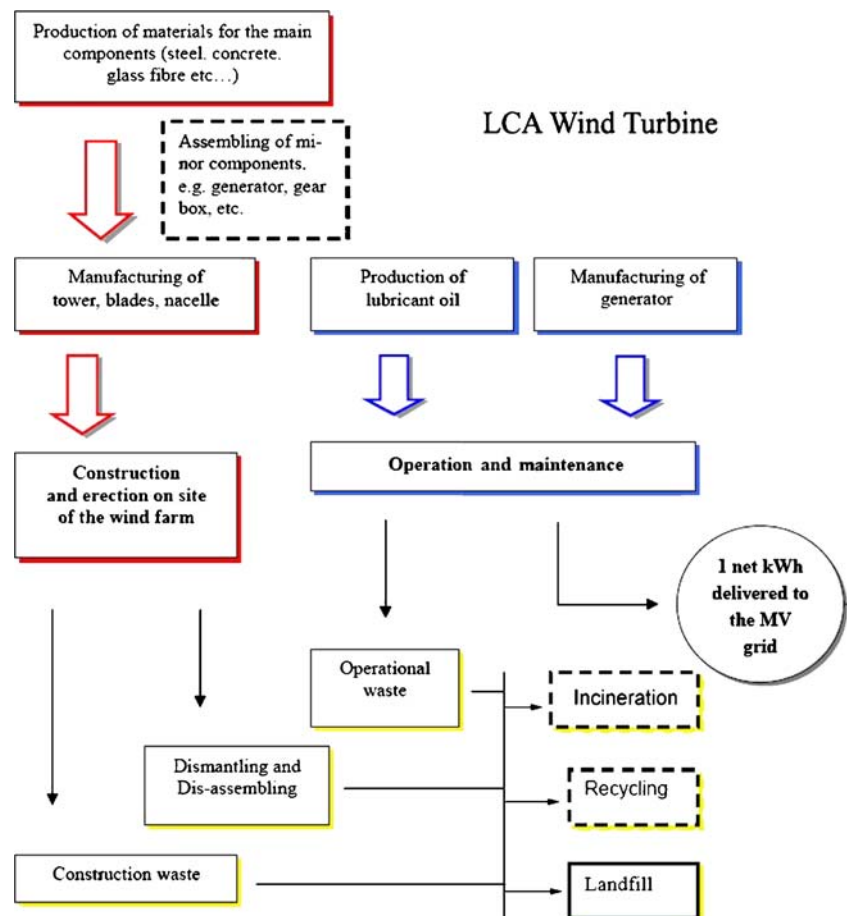**Fig. 2** LCA model of a wind turbine

Table 1 Inventory per component

Component	Subcomponent	Weight	Materials	Energy	Component	Subcomponent	Weight	Materials	Energy
Rotor	3 blades	19.5 T	11.7 T resin	20.15 MWh	Nacelle	Bed Frame	10.5 T	10.5 T iron	9 MWh
			7.8 T fibre glass			Main shaft	6.1 T	6.1 T steel	5.3 MWh
	Blade Hub	13 T	14 T cast iron	12 MWh		Transformer	5 T	0.15 T silica	200,000 MJ
	Nose-cone	310 kg	0.12 T fibre glass	0.95 MWh				1.5 T copper	
			0.19 T resin					3.3 T steel	
Foundation	Footing	725 T	700 T concrete	0.4 MWh		Generator	6.5 T	0.20 T silica	265,000 MJ
			25 T iron					2 T copper	
	Ferrule	15 T	15 T steel	17,000 MJ				4.29 T steel	
Tower	3 sections	143 T	143 T steel	170,000 MJ		Gearbox	16 T	8 T iron	495,000 MJ
								8 T steel	
						Nacelle Cover	2 T	0.8 T fibre glass	6.2 MWh
								1.2 T resin	

turbine, that is, the medium-voltage wiring, the transformer substation and the national electrical power network.

2.3 Functional unit

The aims of the work are to know the environmental impact of wind power and to quantify it, but it is necessary to relate this impact to the electricity generated in order to be able to make a posterior comparative study with regard to other types of energy producing technology. Thus, the functional unit has been defined as the production of 1 kWh of electricity.

2.4 Data collection

A wind turbine consists of many components, which also comprise many sub-components, of different nature and eventually with mechanical, electrical and electronic parts; therefore, it is difficult to gather from suppliers the information on all the parts that compose the turbine.

We have focused on compiling the life cycle inventory (LCI) data on the most important components, specifically the foundation, the tower, the nacelle and the rotor. In addition, in the few cases in which the data found have not been sufficiently reliable and proven, quasi-process information from commercial Ecoinvent database of SimaPro software has been used.

For instance, the materials and energy used in the diverse components have been incorporated into the model using data provided by Gamesa. The distances of transport have been calculated from specific maps as far as the real emplacement of the Munilla wind farm. The main materials that constitute the most important components of the turbine and the selected reference database Ecoinvent can be seen in Tables 1 and 2. Data have been selected at Spanish (country code ES) or European (code RER) levels, wherever possible, in the database Eco-invent v1.3 of

December 2006. With regard to the energy involved in the production processes, the 'Electricity, medium voltage, at grid/ES' option of that database has been considered, always looking for the best similarity with respect to actual production in different factories in Spain. Specific data on energy consumption of manufacturing processes of the various components have been obtained from the annual electricity consumption data of different manufacturing plants of such components.

The owner company of the wind farm performs the maintenance operations, and the information about them is recorded in its environmental management system according to the ISO 14001 standard. Based on this important information, all the maintenance operations have been taken into account during the operational phase, such as quantities of oil and grease used or replacement of filters and transport, among others. Transport processes include the impact of emissions caused by the extraction and production of fuel and the generation of energy from that fuel during transport (Spielmann and Scholz 2005). The 'tkm' has been assumed as a functional unit for transport, which is the transport of 1,000 kg goods over 1 km (Banister et al. 2000).

In the case of the foundation, the possible emissions from the foundation into the environment during the

Table 2 Ecoinvent process selected per material

Material	Ecoinvent process selected
Fibreglass/resin	Glass fibre reinforced plastic, polyamide, injection molding, at plant/RER U
Iron	Cast iron, at plant/RER U
Steel	Reinforcing steel, at plant/RER U
Concrete	Concrete, exacting, at plant/CH U
Silica	MG-silicon, at plant/NO U
Copper	Copper, at regional storage/RER U

lifespan of the wind turbine have not been considered. A recycling of the foundation at 100% for cement and 90% in steel and iron has been supposed at the end of the turbine lifetime.

In the case of the tower, only the processes of shaping and welding steel have been considered in the study. The surface treatment was considered as irrelevant with regard to the final result of the analysis. It is supposed that during the operation of the wind turbine, no maintenance will be

needed in the tower and, in its decommissioning process, the material undergoes a recycling process in which an average material loss rate of 10% has been assumed (Young et al. 2006).

The nacelle is a main element of the wind turbine whose structure consists of a bed frame and a nacelle cover made of a composite material named prepreg. The main components of the turbine responsible for converting the mechanical rotational energy of the rotor into electrical power, which are

Table 3 Detailed LCI of the cone and the hub of the rotor

Subassembly phase product materials	Rotor cone processes	Amount	Unit	Information reference
Fiberglass/resin	General	0.31	T	Data obtained from Gamesa.
				Technical Instruction: Characteristics and overall functioning of the G80–2.0 MW wind turbine
Electrical energy	Manufacture	0.10, Total: 3.1	kWh/kgkWh	The data used were collected from the energy consumption summary table of natural resource extraction and the production of materials of the study, developed by the Polytechnic University of Catalonia, named "estimate of energy consumption and CO_2 emissions associated with the production, use and final disposal of sheeting PVC-P, EPDM and bituminous materials"
	Transport	48,360	kgKm	The transport of the iron of the cone has been considered. The origin of the cone is Pamplona, at 156 km from Munilla. The weight of each unit component considered is 1 kg
				Table 5 shows the consumption due to transportation.
				Distances from different origins to Munilla have been calculated from: www.viamichelin.es
Phase product materials	Hub processes	Amount	Unit	Information references
Cast iron	General	12,890	T	Data obtained from Gamesa.
				Technical Instruction: Characteristics and overall functioning of the G80–2.0 MW wind turbine (page 26)
				It has been calculated as the difference between the total weight of the rotor minus the weight of the blades (19.5 T=6.5×3) and the cone (0.31 T)
				Table 5 shows a breakdown of the consumption due to transportation
Natural gas	Foundry	13,890, Total: 179,042	Kwh/T Kwh	Data processing of the company Precicast Bilbao, in the Basque Country (Spain), dedicated to the production of special super alloys through the process of accuracy casting by lost wax techniques
				It is equipped with technology for casting processes of air and vacuum as well as other similar industrial processes with the aim of producing precision castings
				Environmental declaration Precicast 2005 (Oct 2006) validated by Bureau Veritas according to Regulation (CE 761/2001)
Electrical energy	Foundry	14,356, total: 185,049	Kwh/T Kwh	Environmental declaration Precicast 2005 (Oct 2006) validated by Bureau Veritas according to Regulation (CE 761/2001)
Electrical energy	Mechanization			Rejected
	Transport	2,010,840	kgKm	The transport of the cast iron of the hub has been considered
				The origin of the hub is Pamplona, at 156 km from Munilla. The weight of each unit component considered is 1 kg
				Table 5 shows the consumption due to transportation.
				Distances from different origins to Munilla have been calculated from: www.viamichelin.es

the main shaft, the gearbox, the generator and the transformer, can be found inside the nacelle. The use and maintenance phase includes a complete oil change on the gearbox and the cooling system, as well as regular lubrication of the gears and other mechanical parts of the system. In the decommissioning phase, it is considered that no component is to be reused and that they undergo a recycling process, with a 10% loss of material.

Finally, in the case of the rotor, the nose-cone is also made of prepreg material and the blades (which are 39 m long), while the blade hub is made of cast iron. In the decommissioning process, all the prepreg from the nose-cone and the rotor blades will be sent to landfill (Rieradevall et al. 1997), while the blade hub will be recycled.

Up to this point, the main aspects considered in the LCI of the wind turbine have been described in general terms, without deepening into the details of each component. The processes, materials, energy and calculations taken into account in one of these components, namely the rotor, are described in detail below as an example.

2.4.1 Rotor

Tables 3, 4 and 5 provide details of the aspects considered within the LCI rotor and more specifically the cone and the hub.

2.5 Key assumptions

As previously mentioned, the LCA model developed includes both the turbine and the foundations that support it but not the system for connection to the grid (medium voltage lines and transformer substation).

A series of cut-off criteria have been established in order to develop the study, by defining the maximum level of detail in the gathering of data for the different components of the wind turbine. The main cutoff criterion chosen is the weight of each element in relation to the total weight. This limitation in data collection does not mean a significant weakening of the final results obtained but allows us to streamline, facilitate and adjust the LCA study to make it more flexible.

The characterisation of each component has been obtained from the most important basic data of the manufacture, which are the raw material required, the direct

Table 4 Weight of the components of the rotor

Material	TN	Units	Weight
Blades	6.50	3	19.50
Hub+bearings	12.89	1	12.89
Cone	0.31	1	0.31
Total rotor			32.70

Table 5 Transport of the rotor

Material	Weight (kg)	Origin	Distance (km)	T/km (kg/km)
Blades	19,500	Pamplona	156	3,042,000
Hub+bearings	12,890	Pamplona	156	2,010,840
Cone	310	Pamplona	156	48,360
Total rotor				5,101,200

consumption of energy involved in the manufacturing processes and the information of transport used. The information published by Riso National Laboratory has been used when it was not possible to obtain the energy cost of the manufacturing process directly. This information for specific substances includes the primary energy consumption use related to the production, transportation, and manufacture of 1 kg of material (Etxeberria et al. 2007).

Thus, this LCA has been performed under the following conditions, due to limitations of time and cost:

- The cut-off criterion used has been the weight of the components. The elements that have been taken into account, altogether, make up 95% of the foundations, 95% of the tower and 85% of the nacelle and rotors.
- All data on electricity has been obtained from the SimaPro database (Frischknecht and Rebitzer 2005; Frischknecht et al. 2005).
- The wind turbine lifetime is 20 years. The reason for this election is that this is the period usually guaranteed by the manufacturers and, therefore, used in the viability analysis of wind farms.
- The assumed current recycling rate of waste wind turbine (Table 6) has been estimated based on the wind farm decommissioning projects prepared by the company (GER 2004). This decommissioning process takes place after 20 years, i.e. after the 20 years of lifespan of the wind turbine.
- The production is 4 GWh per wind turbine and year. It is a realistic representation of production, based on 2,000 full load hours per year, used as a reference value for an economically viable wind farm.

Table 6 Type of dismantling

Material	Type of dismantling
Iron	Recycling with a loss of 10%
Fiberglass	Landfill 100%
Oil	Incinerated 100%
Plastics—PVC	Landfill 100%
Other plastics	Incinerated 100%
Rubber	Incinerated 100%
Steel	Recycling with a loss of 10%
Cupper	Recycling with a loss of 5%

Table 7 Characterization results

Impact category	Unit	Total	Maintenance	Tower	Foundation	Rotor	Nacelle
Abiotic depletion	kg Sb eq	3.75E−05	2.78E−06	7.28E−06	4.39E−06	1.88E−05	4.33E−06
Global warming (GWP100)	kg CO$_2$ eq	6.58E−03	3.51E−04	1.35E−03	1.56E−03	2.61E−03	6.96E−04
Ozone layer depletion (ODP)	kg CFC-11 eq	5.21E−10	4.98E−11	1.41E−10	8.69E−11	1.83E−10	6.11E−11
Human toxicity	kg 1,4-DB eq	1.55E−02	6.48E−03	1.40E−03	3.63E−04	4.36E−04	6.84E−03
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	2.81E−03	8.19E−05	1.65E−03	4.00E−04	2.43E−04	4.43E−04
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.41E+00	3.25E−01	1.69E+00	4.48E−01	1.04E+00	9.26E−01
Terrestrial ecotoxicity	kg 1,4-DB eq	1.56E−04	2.78E−05	4.89E−05	1.48E−05	1.55E−05	4.99E−05
Photochemical oxidation	kg C$_2$H$_4$	2.13E−06	5.10E−07	1.84E−07	1.06E−07	6.75E−07	6.51E−07
Acidification	kg SO$_2$ eq	5.43E−05	7.64E−06	5.34E−06	3.53E−06	1.94E−05	1.84E−05
Eutrophication	kg PO$_4$— eq	5.68E−06	3.24E−07	1.71E−06	8.25E−07	1.91E−06	8.98E−07

- One replacement generator has been estimated during the complete lifetime of the wind turbine.

According to the requirements of the standard ISO14044 (ISO 2006), allocation has been avoided, since in this study, only the production of electrical power is considered as the function of the system, and therefore, allocation has not been considered in any component or process.

3 Results

3.1 Environmental impact

The results obtained per impact category are shown in Table 7.

If these results are compared with the environmental impact generated by producing the same power level in the Spanish electrical system, i.e. by using the electricity mix in Spain from the database Ecoinvent, a remarkable trend can be noticed, which is a lower impact associated to wind turbine for every category. The percentage reduction of environmental impacts of the electricity generation from wind turbine versus the Spanish mix study can be seen in Table 8. However, we must also bear in mind, in the database Ecoinvent, that the country mixed electricity is established with the average production of the year 2000; therefore, the remarkable increases in recent years for renewable energy in Spain are not appreciated, but the gap and the trends are made clear.

Another result to assess from an environmental point of view is the effect of dismantling and subsequent treatment of waste at the end of the turbine lifetime. The result obtained for recycling each of the major components of the wind turbine can be seen in Table 9. In general, a greater environmental benefit due to the recycling of the tower, more specifically the steel that composes it, can be observed, and in the opposite case, the recycling of rotor is located, since blades, which are one of its main components, are not recycled but directly sent to landfill. This treatment at the end of the

lifespan of waste from the blades is what is used in Spain today, but it is very likely to change in the near future. As an alternative scenario, an 80% recycling of composite material of the blades has been considered in a sensitivity analysis (see Section 4.3). This will assess future changes concerning the trend of composite materials recycling, since the current rules begin to consider a disadvantage sending such material to landfill. It is also noteworthy that the static approach of LCA (Pehnt 2006) does not take into account any change to the country mixed electricity used, and hence, the alterations that this may involve in the environmental benefit of the studied recycling processes are not assessed.

3.2 Cumulative energy demand

The CED is calculated for five classes of primary energy carriers: fossil, nuclear, hydro, biomass and others (wind, solar and geothermal). Differences for different types of cumulative energy demands are mainly due to the consideration of location-specific electricity mixes. The preponderance of non-renewable energies in Spain, especially energy from fossil fuels, is clearly demonstrated (Table 10). On the other hand, looking at the major components, the

Table 8 Percentage reduction of environmental impacts of wind turbine versus the electricity mix of Spain

Impact category	% reduction of environmental impact
Abiotic depletion	98.99
Global warming (GWP100)	98.76
Ozone layer depletion (ODP)	96.73
Human toxicity	89.26
Freshwater aquatic eco-toxicity	94.06
Marine aquatic eco-toxicity	99.34
Terrestrial eco-toxicity	92.68
Photochemical oxidation	99.24
Acidification	99.28
Eutrophication	97.78

Table 9 Environmental impact prevented by recycling

Impact category	Unit	Tower recycling	Foundation recycling	Rotor recycling	Nacelle recycling	Total recycling
Abiotic depletion	kg Sb eq	2.28E−05	6.26E−06	2.14E−06	6.58E−06	3.78E−05
Global warming (GWP100)	kg CO2 eq	1.65E−03	4.53E−04	1.53E−04	4.96E−04	2.75E−03
Ozone layer depletion (ODP)	kg CFC-11 eq	2.59E−11	6.39E−12	1.13E−12	1.08E−11	4.41E−11
Human toxicity	kg 1,4-DB eq	7.30E−04	2.01E−04	6.88E−05	8.41E−04	1.84E−03
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	3.90E−04	1.08E−04	3.76E−05	2.16E−04	7.53E−04
Marine aquatic ecotoxicity	kg 1,4-DB eq	9.86E−01	2.74E−01	9.49E−02	3.94E−01	1.75E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	6.10E−06	1.69E−06	5.80E−07	4.34E−06	1.28E−05
Photochemical oxidation	kg C_2H_4	1.61E−06	4.49E−07	1.55E−07	5.06E−07	2.73E−06
Acidification	kg SO_2 eq	8.28E−06	2.26E−06	7.59E−07	4.18E−06	1.55E−05
Eutrophication	kg PO_4^- eq	1.20E−06	3.26E−07	1.08E−07	4.43E−07	2.08E−06

biggest impact can be observed in the rotor, mainly due to the manufacture of the turbine blades.

4 Discussion

4.1 Process contribution

Three major components mainly contribute to the environmental effect: rotor, tower and nacelle. The greater or lesser impact of each of these components varies depending on the category of impact that has been valued, but, in general, some trends appear:

- In the case of the rotor, the largest environmental impact is determined by the amount of fibreglass used in the manufacture of the blades and the cone. This impact is accentuated by sending the material to recycle at the end of the turbine lifetime.
- In the case of the tower, the key element is the steel used in its manufacture. However, despite the significant amount of material used, its final impact is reduced because of the 90% material recycling in the phase of

dismantling and disposal of the turbine, but the sending to landfill of the 10% of remaining steel represents a significant impact in categories such as freshwater aquatic, eco-toxicity, and marine aquatic eco-toxicity, due mainly to the time horizon for the valuation of these categories is infinite.

- In the case of the nacelle, the copper used in the various elements that constitutes it presents special incidence, as well as the fibreglass used in manufacturing the casing.
- The percentage of environmental impact associated with each component category can be seen in Fig. 3.

4.2 Energy payback time

Another important aspect is to evaluate the energy payback and energy yield ratio. The definition of both terms is as follows:

- Energy payback time: This term indicates the years that the system under study must be operating to return the amount of energy that has been needed for their
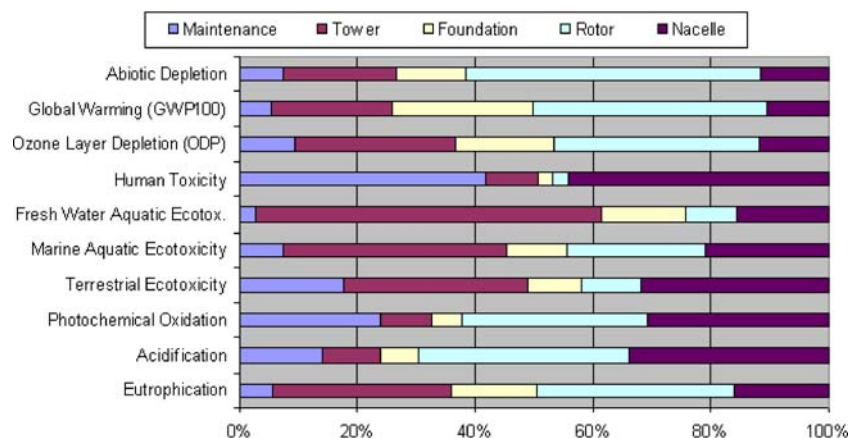
Fig. 3 Process contribution per impact category

Table 10 Cumulative energy demand results

Impact category	Unit	Total	Maintenance	Tower	Foundation	Rotor	Nacelle
Non-renewable, fossil	MJ-Eq	7.63E−02	6.03E−03	1.62E−02	9.30E−03	3.60E−02	8.81E−03
Non-renewable, nuclear	MJ-Eq	2.22E−02	7.22E−04	6.51E−03	2.67E−03	9.15E−03	3.18E−03
Renewable, biomass	MJ-Eq	1.14E−03	1.12E−04	2.80E−04	1.38E−04	3.24E−04	2.88E−04
Renewable, wind, solar, geothe	MJ-Eq	7.13E−04	1.49E−05	1.61E−04	4.74E−05	3.60E−04	1.30E−04
Renewable, water	MJ-Eq	4.39E−03	3.77E−04	1.13E−03	7.04E−04	1.15E−03	1.03E−03

manufacture, start-up and operation throughout its lifespan.

- Energy yield ratio: This term represents the relationship between the energy generated by the system throughout its lifetime and the energy consumed by the system (CED).

Table 10 showed the CED value of the wind turbine. From this basis and with an average annual production of wind turbine of up to 4,000 MWh (Troen and Petersem 1991), an energy payback time of 0.58 years and an energy yield ratio of 34.36 are obtained.

In addition, the time needed to compensate for the environmental impact generated by manufacturing, launching and operating of wind turbines, by the reduction of requirements for conventional electric energy generation has been calculated. This study has considered again the electricity mix in Spain from the database Ecoinvent. The obtained result varies from 53 to 784 days according to categories.

4.3 Sensitivity analysis

The different uncertainties arising from the options given during the development of the LCA of a wind turbine have been analysed. Looking always to cover the largest possible spectrum of options, four scenarios have been analysed, focusing on four main phases of lifecycle: maintenance (higher maintenance), manufacturing (increase of 10% in the area of materials and energy), dismantling (half the recycling) and recycling (recycling of 80% of the composite material of the blades).

In addition, the impact that these scenarios may present on the final LCA has also been assessed. In Table 11, a summary of the sensitivity analysis that has been performed, per different impact category, can be seen. The table shows the minimum and maximum values for each category and the value of the basic scenario.

The sensitivity analysis conducted shows variations in the final results ranging from 10% for the category of human toxicity up to 71% for the category of photochemical oxidation. The alternative scenario that has the greatest impact on the final result is the one related to the increase of maintenance; this is so because this scenario provides for an increase in major corrective, with the corresponding need for manufacturing of large wind turbine components such as the gearbox and the blades.

5 Conclusions

Throughout this article, the environmental impact generated by a wind turbine has been analysed. From the results obtained, an important conclusion is the significant impact generated by the turbine blades and, especially, their non-recycling status. Here is found a need for further research into recycling processes of this type of material (Pickering 2006; Cunliffe et al. 2003; de Marco et al. 1997; Torres et al. 2000; Williams et al. 2005; Vallee et al. 2004; Perrin et al. 2006), as well as for their practical application in the final dismantling and waste treatment phases of wind turbines. Another material that presents a significant impact

Table 11 Summary of the sensitivity analysis by categories

Impact category	Unit	Base	Max	Min
Abiotic depletion	kg Sb eq	3.75E−05	5.71E−05	3.33E−05
Global warming (GWP100)	kg CO_2 eq	6.58E−03	9.29E−03	6.20E−03
Ozone layer depletion (ODP)	kg CFC-11 eq	5.23E−10	7.24E−10	5.23E−10
Human toxicity	kg 1,4-DB eq	1.55E−02	1.70E−02	1.55E−02
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	2.81E−03	3.23E−03	2.81E−03
Marine aquatic ecotoxicity	kg 1,4-DB eq	4.41E+00	5.36E+00	4.41E+00
Terrestrial ecotoxicity	kg 1,4-DB eq	1.56E−04	1.73E−04	1.54E−04
Photochemical oxidation	kg C_2H_4	2.13E−06	3.54E−06	2.03E−06
Acidification	kg SO_2 eq	5.43E−05	7.31E−05	5.13E−05
Eutrophication	kg PO_4^- eq	5.68E−06	7.69E−06	5.36E−06

within the study is the copper (Lunt et al. 2002; Norgate and Rankin 2000) present in the nacelle of the turbine but, in this case, with the advantage of being a recyclable material (Norgate et al. 2007).

In any case, although there are components with a significant environmental impact within the turbine, it has also been verified that these impacts are much smaller than those generated by conventional power plants in operation, with reductions in the impact ranging from 89% to 99%, depending on the category. In addition, the energy payback time (time regarding the energy required to produce and implement a turbine) is less than 1 year, much smaller than the useful lifetime of the system, which is at least 20 years.

6 Recommendations

Undoubtedly, the use of wind energy farms to produce electricity constitutes an environmental improvement over other conventional sources of electrical energy. This does not mean that it is not necessary to further deepen and develop this technology, especially if we bear in mind its recent growth and future prospects (del Río and Unruh 2007; Jäger-Waldau 2007; Karki 2007; GWEC 2005; Elamouri and Ben Amar 2008; Yuksel 2008; Sailor et al. 2008; Dutra and Szklo 2008; Papadopoulos et al. 2008). For example, it remains necessary to explore in more detail and seek ways of improving the manufacturing processes of the wind turbine and its components, as well as concerning possible ways to reuse or recycle different materials and components. More than anything, however, it is critical that large wind turbine manufacturers understand the advantages and opportunities offered by the use of LCA in their products, both for the continuous improvement of processes and products (Muñoz et al. 2006) and from a commercial point of view (Mila i Canals et al. 2002; Marchenko 2008).

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